U. S. NAVAL AIR DEVELOPMENT CENTER

Johnsville, Warminster, Pennsylvania

Report No. NADC-AE-6721 15 JUN 1967

VARIABLE PARAMETER POWER SOURCE

FINAL REPORT
AIRTASK NO. A36533305/2021/F008-02-01
Work Unit No. 12

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DEPARTMENT OF THE NAVY
U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
WARMINSTER PA 18974

Aero-Electronic Technology Department

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A variable parameter power source was designed and fabricated to provide a 30-kva 3-phase source of power with controllable voltage modulation, frequency modulation and harmonic content for the purpose of simulating these power characteristics as described in MIL-STD-704.

Reported by: E. C. Lesoravage
E. C. Lesoravage
Electrical Division

Approved by: L. M. Cobb
L. M. Cobb, Superintendent
Electrical Division

M. J. Madigan
M. J. Madigan
Acting Director

S U M M A R Y

INTRODUCTION

AIRTASK No. A3653330S/2021/F008-02-01, Work Unit No. 12 requested the NAVAIRDEVCEN to develop a 30-kva, 3-phase, 4-wire power source to serve as a laboratory instrument in which as many of the power characteristics of MIL-STD-704[1] as are practicable are variable and controllable. The need for a laboratory power source of this type is based on analyses of malfunctions in aircraft systems which have indicated that certain power system characteristics induce the malfunctions. The development of a laboratory power source in which the suspected parameters can be controlled and varied will facilitate the determination of the individual effects of these characteristics on aircraft systems.

SUMMARY OF RESULTS

The variable parameter power source developed at NAVAIRDEVCEN was designed to provide a 30-kva, 4-wire source of 400-hz power with controllable and variable voltage modulation, frequency modulation, and harmonic content. Voltage and frequency modulation are each controllable with respect to the amplitude of modulation and with respect to the repetition rate of the modulation envelope about any frequency between 380 and 420 hz over the range specified by MIL-STD-704. Harmonic content is controllable with respect to the amplitude of the individual 3rd, 5th, 7th, 9th, and 11th harmonics and with respect to the phase relationship of each of these harmonics to the fundamental output of the primary power supply through 360 degrees of each harmonic's period. Harmonics may be introduced to the power system and controlled singularly to provide an individual harmonic content of 0 to 5 percent at 50 percent of system load. Combinations of harmonics may also be introduced to produce a range of total harmonic content of 0 to 8 percent. A 30-v, 200-amp d-c power supply is also provided as part of the total variable parameter power source package.

CONCLUSIONS

The variable parameter power source was operated as a complete system and its performance was considered to have satisfied the design objectives regarding voltage modulation and frequency modulation. The capabilities of the harmonic producing section are considered to exceed the design objectives for harmonic content, and should prove adequate to satisfy any additional requirement imposed by future changes to MIL-STD-704. It is therefore concluded that the techniques employed in the development of the variable parameter power source have been justified.

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1. *MIL-STD-704; Electric Power, Aircraft, Characteristics and Utilization of; UNCLASSIFIED.*

RECOMMENDATIONS

It is recommended that the present variable parameter power source, particularly the harmonic producing section, be used as the basis for construction of an "advanced-design" power source which will incorporate additional controllable parameters. It is recommended that the following parameters be considered for inclusion in the "advanced-design" power source:

1. Phase angle displacement
2. Unbalanced phase voltages
3. Transient voltages
4. Frequency drift
5. Transient frequencies
6. Abnormal system interruptions

The inclusion of these parameters will afford the capability of more completely simulating the conditions described in MIL-STD-704.

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GENERAL

The variable parameter power source developed at NAVAIRDEVCEN and illustrated in figure 1 consists of a 60-hp induction motor, electronic clutch with solid state speed control, a 30-kva brushless alternator controlled by a static regulator, a harmonic generating section, power amplifier section, and a solid state 200 amp, 28 v d-c power supply. The system contains the necessary instrumentation for measurement of the various parameters. Input power requirements for the system are: 3 phase, 440 v, 60 hz, and 100 amp.

BACKGROUND

The basic power supply consisting of the motor, clutch and alternator was purchased under Contract No. N62269-3092 from the Inet-Sprague Division, Teledyne Incorporated of Gardena, California. This motor-generator set consists of:

1. A 3 phase, 60 hz induction motor manufactured by U.S. Motors which is directly coupled to the electronic transmission assembly.

2. An electronic transmission and speed control circuit manufactured by WER Industrial Corporation which operates on an eddy current principle and which drives the alternator.

3. A brushless, synchronous, three phase, revolving field-generator, with a brushless exciter and a tachometer assembly manufactured by Inet-Sprague Division.

4. A solid state voltage regulator assembly capable of maintaining the desired output voltage level.

5. A solid state modulator assembly which provides the means of controlling voltage and frequency modulation.

6. The magnetic starters, input and output contactors, controls and instrumentation necessary for the operation of this motor generator set.

The entire assembly is housed in a metal enclosure containing removable panels for access to all components. Figure 2 illustrates the basic power supply as provided by Inet-Sprague Division.

The d-c power supply, figure 3, was purchased from Christie Electric Corporation of Los Angeles, California, and consists of a 28 v, 200 amp solid state, mag amp regulated unit of the Christie "Stavolt Type." This supply has a static regulation of ±0.25 percent, dynamic regulation of ±6.5 v zero to full load, and a ripple component of less than 1 percent.

NAVAIRDEVCEN design effort was primarily directed toward the development of the harmonic generating section, the methods of controlling and mixing the generated harmonics with the fundamental voltage for the system, and the instrumentation of all variable parameters. In addition, the 30-kva power supply was modified to provide access to all controls from a central location, a trailer was modified to accommodate the completed power supply components, and all equipment was packaged and mounted on the trailer. The completed harmonic section consists of a source of harmonic voltages for the third, fifth, seventh, ninth, and eleventh harmonics. Each harmonic is controllable with respect to its amplitude and its phase relationship to the fundamental voltage through 360 nth harmonic degrees. Due to the nature of the harmonic generating circuitry, each harmonic is an exact integral multiple of the fundamental frequency when the fundamental frequency varies between 380 and 420 hz. Instrumentation is provided for the direct reading of the harmonic components in terms of absolute or relative values. In addition to the harmonic generating section a mixing filter and filter charging circuit was developed for the combination of the harmonic voltages with the fundamental voltage and circuitry was devised to display amplitude and rate of both voltage and frequency modulation. Figure 4 illustrates the console of the harmonic generating section.

THEORY OF OPERATION

Figure 5 is a block diagram of the variable parameter power source. The 60 hp induction motor is started by magnetic starters in the 3-phase, 440 v line and is directly coupled to the eddy current drive. The eddy current clutch is directly connected to the alternator and rotates the alternator in accordance with the setting of the speed control circuitry. The eddy current clutch rotor assembly output speed varies in accordance with the excitation applied to the stationary field of the clutch and the resulting flux linkages between the drive and the clutch, thereby permitting variations of the output speed. The output voltage and frequency of the brushless alternator is controlled by the solid state voltage regulator and the speed control circuitry associated with the electronic transmission. Control of the 3 phase, 400 hz output voltage is achieved through variations in the d-c excitation applied by the regulator to the stationary field of the exciter and the corresponding changes which occur in the rectified d-c output of the rotating exciter rotor. The output of the exciter rotor is applied to the rotating field of the alternator, thereby controlling the 3 phase, 380 to 420 hz output voltage generated in the stator windings.

Voltage and frequency modulation is produced in the modulation circuit which consists of a Schmitt trigger and integrating amplifier. The resulting linear ramp waveform superimposed on a variable d-c level is applied to the voltage regulator and to the speed control circuitry to provide the desired amount of controllable voltage or frequency modulation.

Figure 6 is a schematic of the harmonic generating section. Harmonic generation is accomplished by clipping the fundamental voltage waveform of a single phase at an angle which maximizes the magnitude of the odd harmonics required. In order to achieve this, a matched pair of 22 v zener diodes and a 5 ohm, 250 w ballast resistor is used to produce a quasi-square wave inherently rich in odd harmonics. A complete mathematical analysis of this circuit is given in Report No. NADC-AE-6508[2]. The output of the clipping circuit is fed to five parallel bandpass filters with center frequencies corresponding to the required harmonics at 1200, 2000, 2800, 3600, and 4400 hz and with 10 percent bandwidths. The signal produced at the output of each filter is then applied to emitter follower amplifiers to produce the necessary voltage gain, amplitude control, and impedance matching between filters and phase resolvers. The respective amplifier outputs are then applied to the inputs of five phase splitter-resolvers manufactured by Theta Instrument Corporation of Saddlebrook, New Jersey. Each of the "Style PG-3" phase generators is designed for the specific harmonic frequency of the circuit in which it is used and resolves a single phase input into a 2-phase output with 90 degrees ±0.1 degree displacement between voltages. The phase generators produce a phase control capability for each harmonic of 0 to 360 degrees with a phase accuracy of 30 min of the dial arc.

The two phase output of each resolver is then applied to a Scott-connected transformer pair for the transformation from a two phase output to a three phase output for each of the harmonics generated. The three phase harmonic outputs are then fed to the summing networks of three negative feedback operational amplifiers in the appropriate positive or negative phase sequence in order to provide a summation of the five harmonics at a controlled signal level and on a three phase basis.

The composite harmonic signal for each phase is then fed into three solid-state power amplifiers, model TP-100-1, manufactured by Ling Electronics Division, LTV Ling Altec Incorporated, Anaheim, California. Each power amplifier is rated at 100 v-amp or 10 amp at a maximum 14 5 v rms output. The amplifiers supply the necessary harmonic power for the required 30-kva load.

Harmonic power is then mixed with the fundamental power through a trio of mixing filters, one for each output phase. These filters consist of parallel combinations of series resonant circuits each tuned for one of the harmonic frequencies. Shunt resonance of each of the filters at 400 hz serves to isolate the power amplifier outputs from fundamental line voltage while maintaining paths for the harmonic power. A sequential

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2. *Garnett, J., 14 Oct 1965; Development of Variable Parameter Power Source; Report No. NADC-AE-6508; UNCLASSIFIED.*

switching circuit in series with the output of the harmonic generator serves to "charge" the mixing filters with 400-hz power prior to placing the harmonic section in parallel across the load and across the supply of fundamental power.

Instrumentation of the variable parameter power source consists of the readout of harmonic content produced, visual displays of voltage and frequency modulation, a-c and d-c voltage and current output and a-c output frequency. The harmonic content is measured with a Dynamic Analyzer SD-101A manufactured by Spectral Dynamics Corporation of San Diego, California. This instrument is a frequency-tuned bandpass filter which relies on a tuning frequency from an external source. In the case of the variable parameter power source this signal is monitored at the amplitude control circuit of the individual harmonic signal sources thereby guaranteeing that the reference signal is an identical frequency to the harmonic voltage to be measured.

Frequency modulation is measured by use of a discriminator circuit consisting of a pair of tuned circuits, rectifiers and a d-c bridge. The differential voltage across the bridge forms an output which is proportional to the change of frequency of the fundamental voltage. This output is displayed on a Hewlett-Packard Model 132A Dual Beam Oscilloscope. Voltage modulation is displayed on the second beam of the same scope by monitoring the peaks of the positive going half cycles of the fundamental voltage output.

PERFORMANCE

Upon completion of the assembly of the variable parameter power source the system was given an operational check-out to determine the output limits of the harmonic generating section. Photographs of the output of each of the harmonic generating stages were taken to demonstrate the effects of maximum amounts of harmonics on the fundamental voltage waveform of one phase of the power source. Figure 7 illustrates the fundamental output of the 30 kva supply prior to the introduction of harmonics. This waveform inherently consists of less than 1 percent total harmonics and no harmonic exceeds 0.5 percent of the 120 v rms value of the fundamental. In figures 7 through 14 data were taken at 50 percent of the system load (15 kva) and at unity power factor in order to approximate system loads anticipated in the immediate future. The traces illustrated are not to scale in the respect that the harmonics were amplified and the 120 v (rms), 400 hz output voltage was attenuated to more vividly display the cause and effect of introducing harmonic voltages into the fundamental output. Figures 8 through 12 illustrate the effect of introducing 6 v or 5 percent of each of the odd harmonics 3 through 11, respectively, into the output voltage at a phase angle which maximizes the influence of the harmonic on the 400-hz output.

Figure 13 illustrates the effects of combining: 6 v or 5 percent of the third harmonic, 4.8 v or 4 percent of the fifth harmonic, 3.6 v or 3 percent of the seventh harmonic, 2.4 v or 2 percent of the ninth harmonic, and 1.2 v or 1 percent of the eleventh harmonic and introducing these harmonics into the power supply output. Application of the formula:

$$D_{total} = \sqrt{D^2{}_3 + D^2{}_5 + D^2{}_7 + D^2{}_9 + D^2{}_{11}}$$

indicates a total harmonic distortion present equal to 7.35 percent of the fundamental output voltage.

Figure 14 illustrates the effect of shifting the phase relationship of a single harmonic (in this case, the fifth) on the output voltage. Trace (A) indicates a zero degree phase relationship between a 5 percent fifth harmonic component and the output voltage. Trace (B) illustrates the effect of a phase shift of 120 fifth harmonic degrees on the output voltage while maintaining a 5 percent fifth harmonic amplitude component. Trace (C) illustrates the effect of a phase shift of 240 fifth harmonic degrees on the output voltage while maintaining a 5 percent fifth harmonic amplitude component. This phase shift capability extends to each of the five controllable harmonics and permits individual control over the phase relationship of each harmonic with respect to the output voltage when introduced singularly or in combination with other harmonics.

Tables I and II are representative of the maximum harmonic generating capabilities at 50 and 100 percent of system load. In each case the harmonic content was measured across all three phases of the load to determine the degree of balance for each harmonic across the three phases of the load.

TABLE I

MAXIMUM HARMONICS PRODUCED AT 50 PERCENT SYSTEM LOAD

Harmonic	Percent of 120 v		
Order	ϕA	ϕB	ϕC
3rd	5.0	5.0	5.0
5th	5.0	5.0	5.0
7th	5.0	4.7	5.2
9th	5.0	5.4	5.5
11th	5.0	5.0	5.0

T A B L E   I I

MAXIMUM HARMONICS PRODUCED AT 100 PERCENT SYSTEM LOAD

Harmonic Order	Percent of 120 v ϕA	ϕB	ϕC
3rd	5.0	4.9	4.6
5th	4.3	4.3	4.3
7th	4.0	3.6	4.0
9th	4.8	4.8	4.8
11th	2.9	2.9	3.1

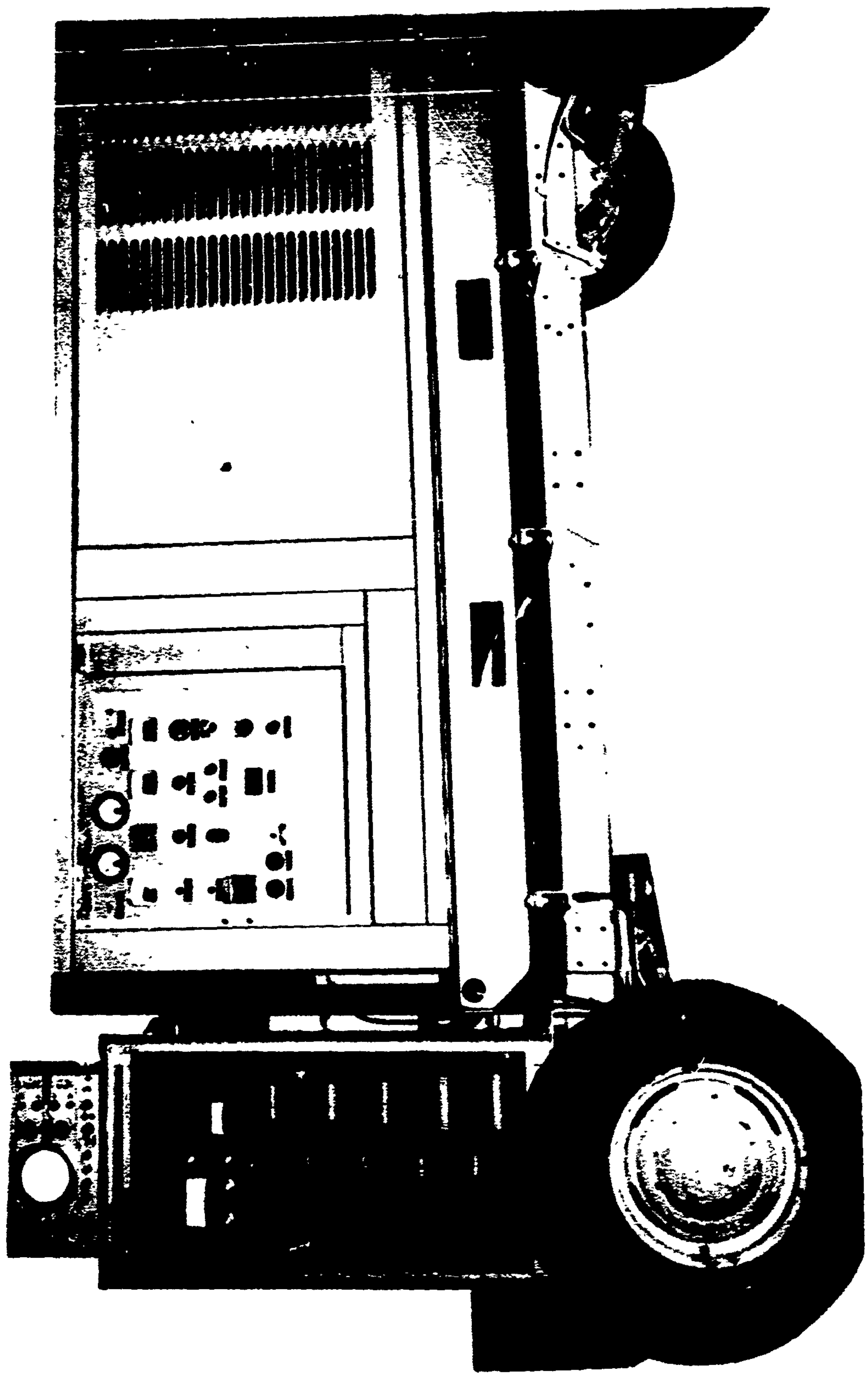

FIGURE 1 - Variable Parameter Power Source Completed Assembly

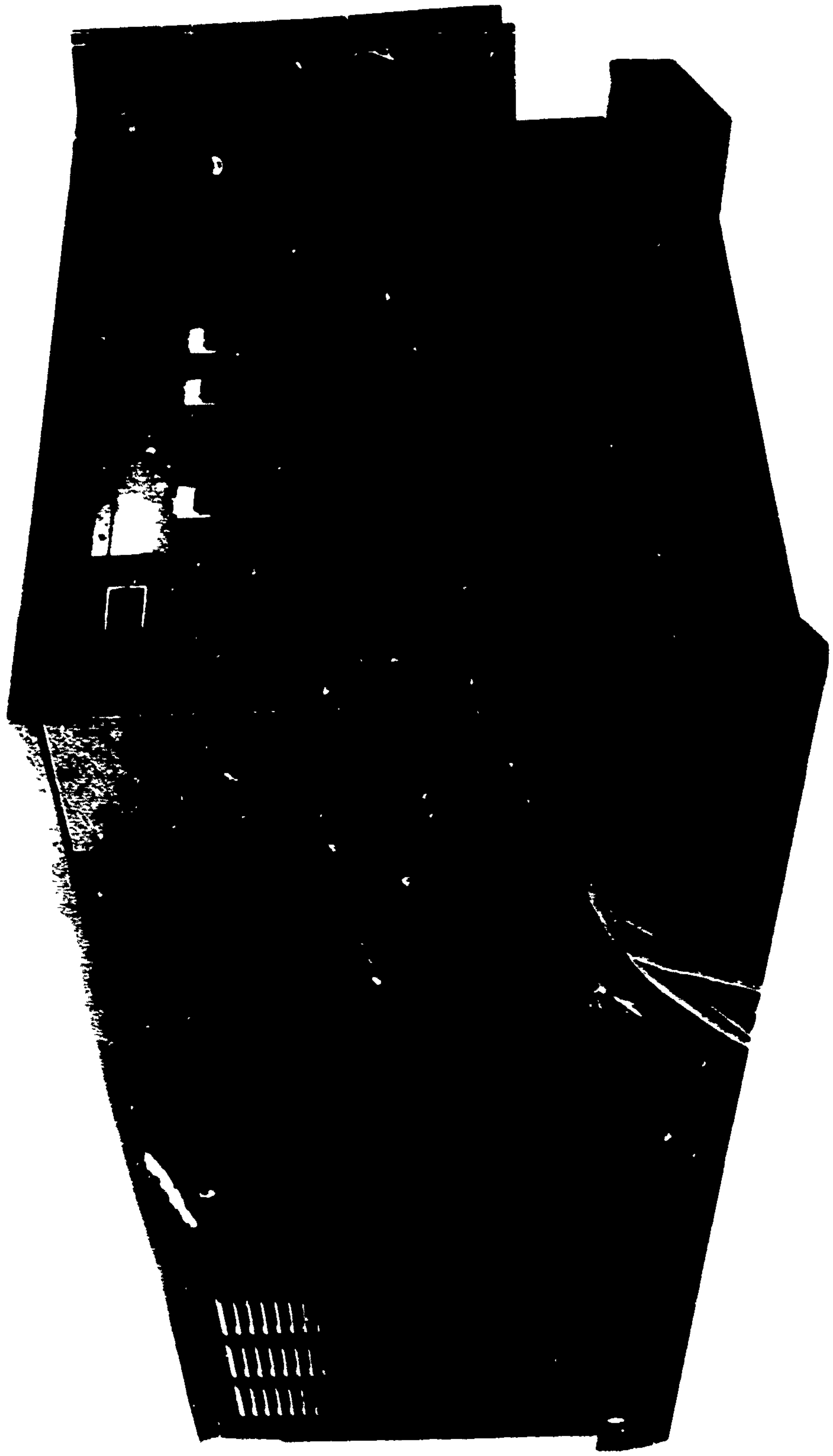

FIGURE 2 - Inet Sprague 30 KVA Power Supply

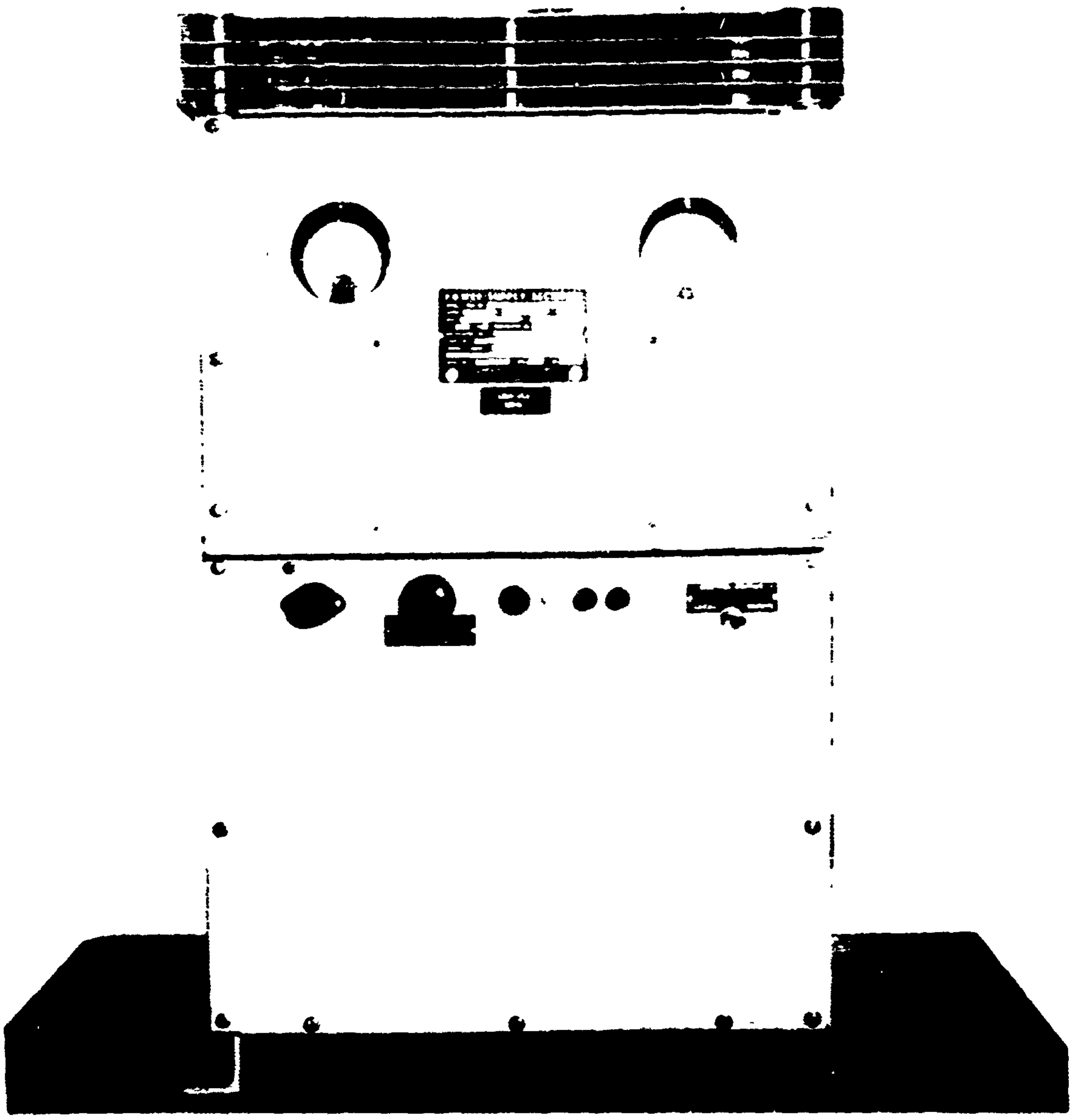

FIGURE 3 - Christie Electric Corporation DC Power Supply

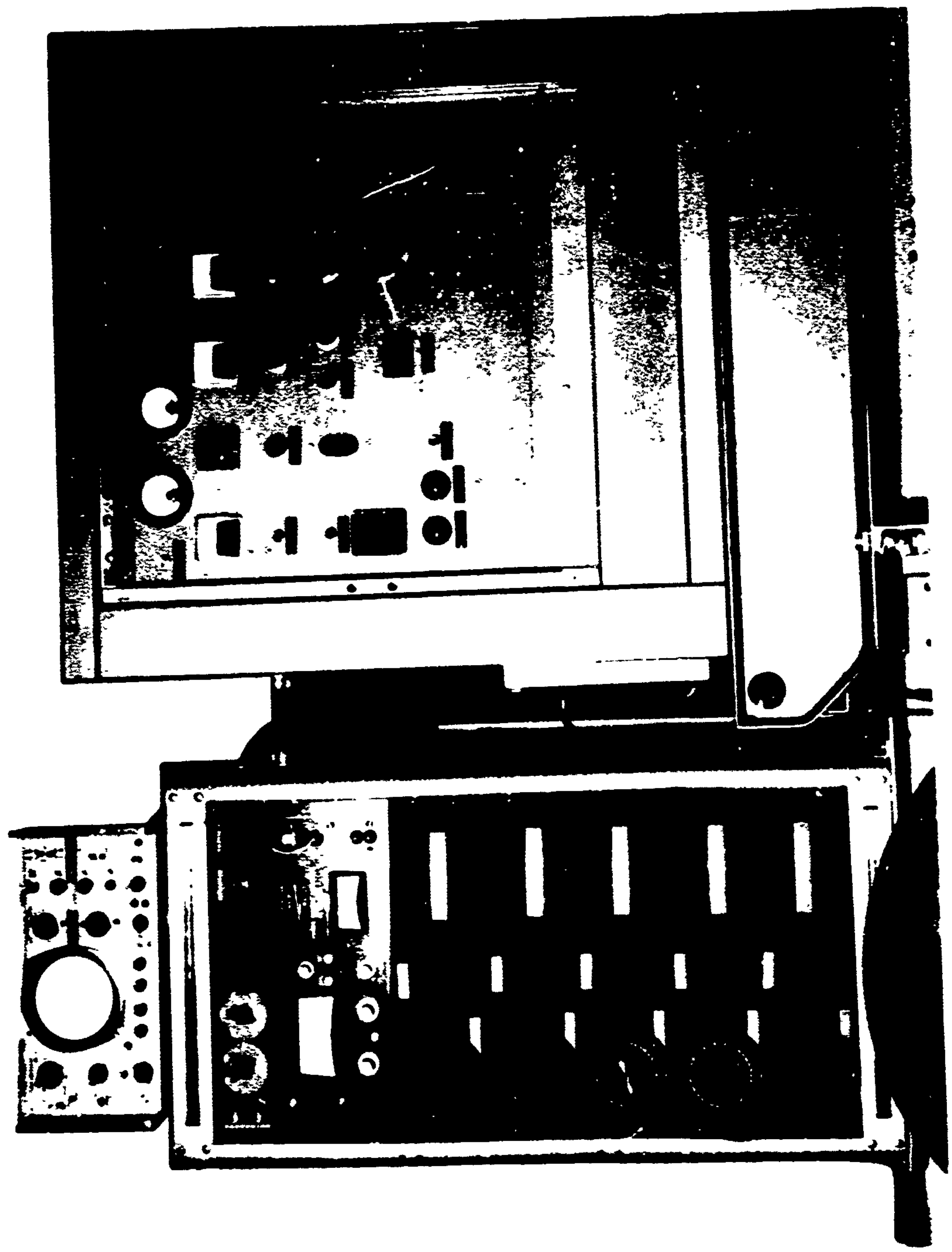

FIGURE 4 - Harmonic Control Console and 400 hz and DC Power Supply

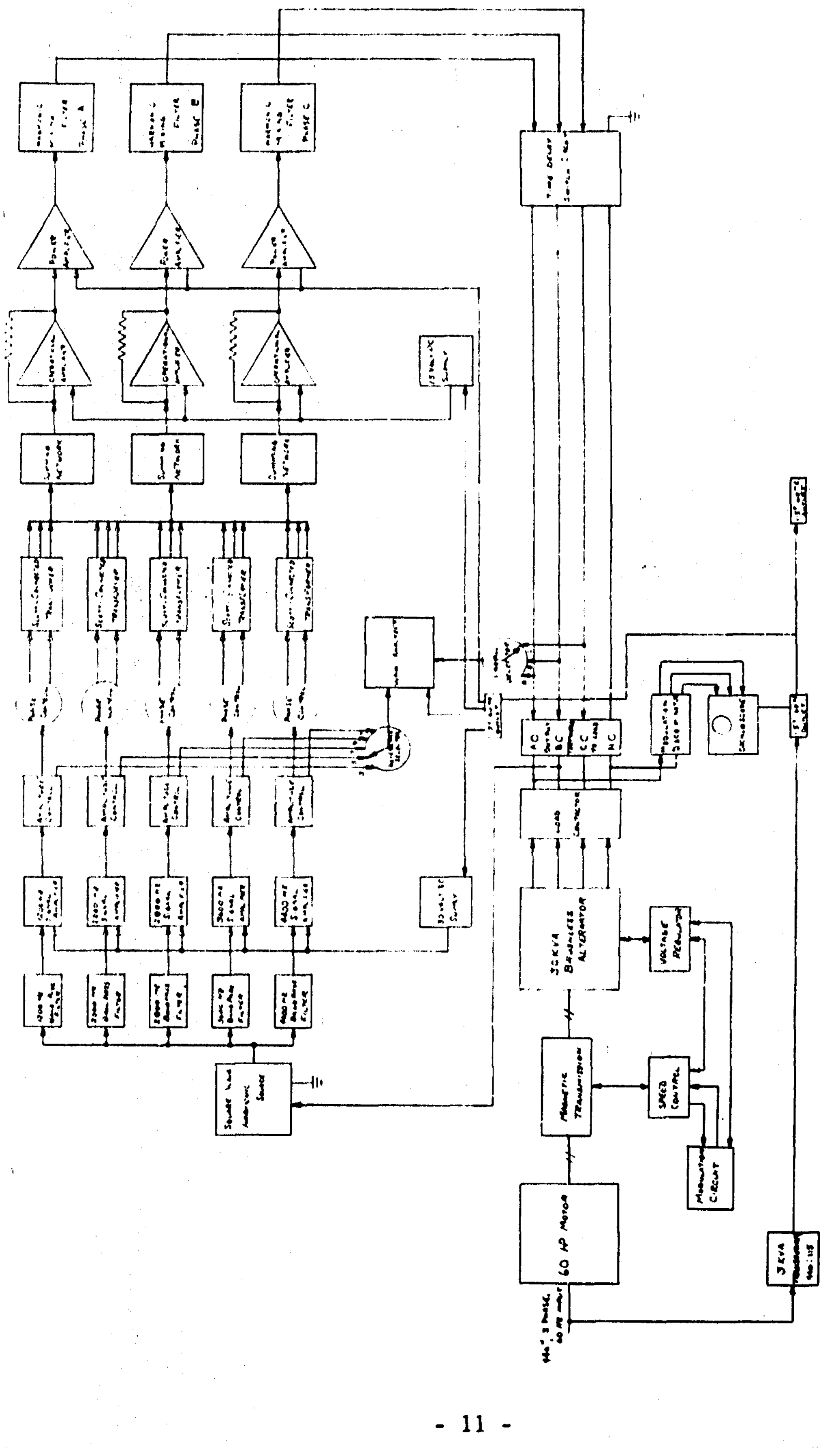

FIGURE 5 - Block Diagram of Variable Parameter Power Source

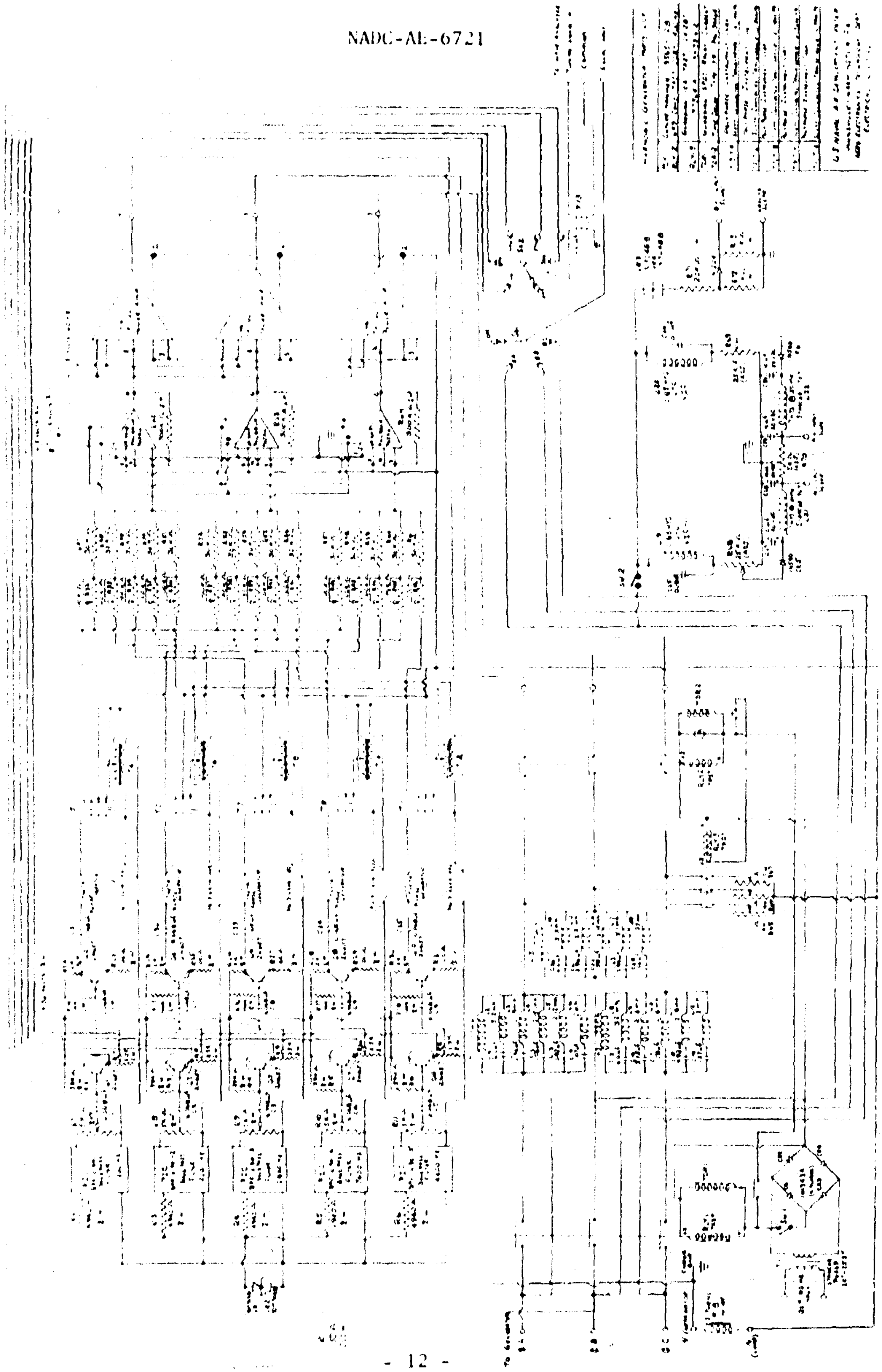

FIGURE 6 - Schematic of Variable Parameter Power Source Harmonic Section

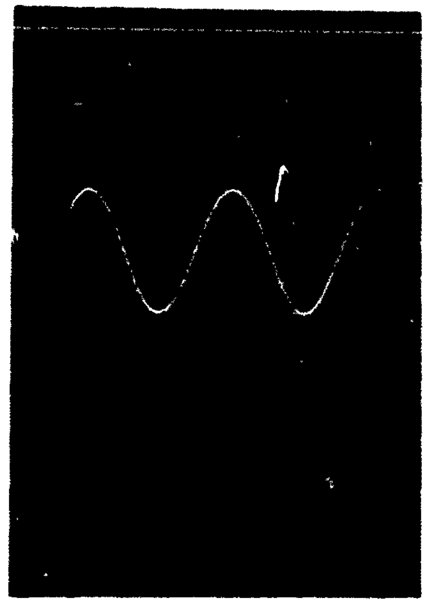

FIGURE 7 - Fundamental - No Harmonics Introduced

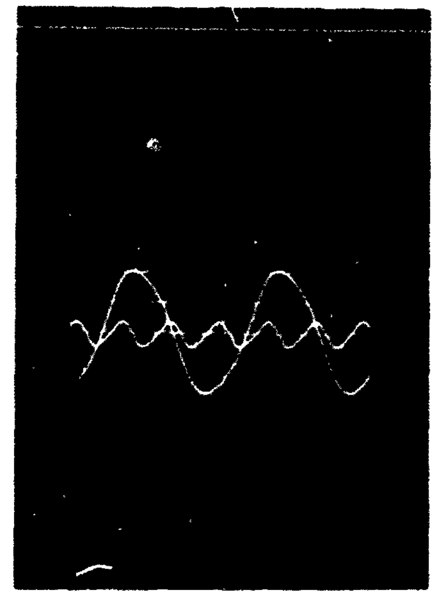

FIGURE 8 - Fundamental +5 Percent 3rd Harmonic

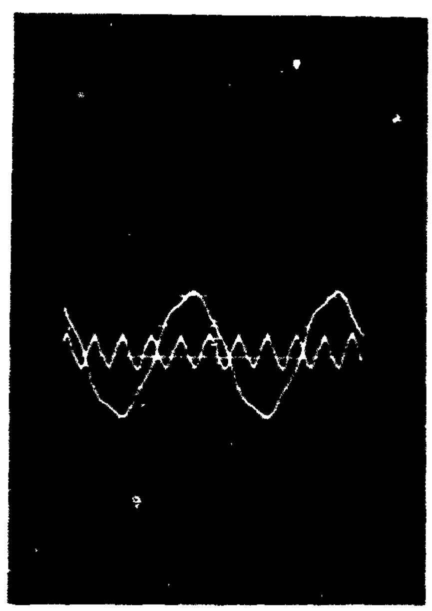

FIGURE 9 - Fundamental +5 Percent 5th Harmonic

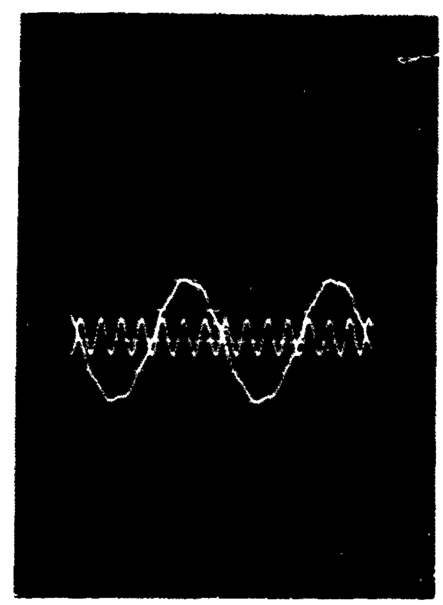

FIGURE 10 - Fundamental +5 Percent 7th Harmonic

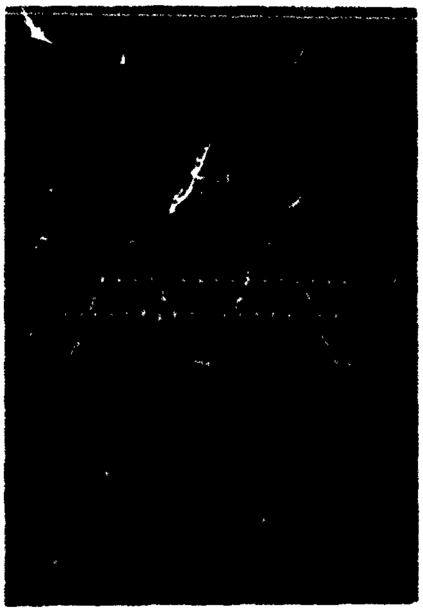

FIGURE 11 - Fundamental +5 Percent 9th Harmonic

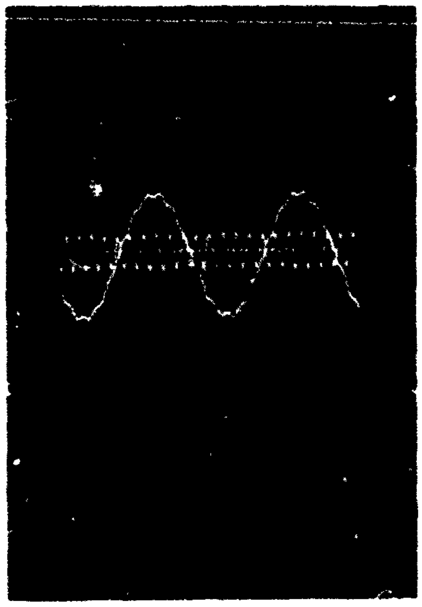

FIGURE 12 - Fundamental +5 Percent 11th Harmonic

FIGURE 13 - Fundamental +5% of 3rd, 4% of 5th, 3% of 7th, 2% of 9th, & 1% of 11th Harmonic

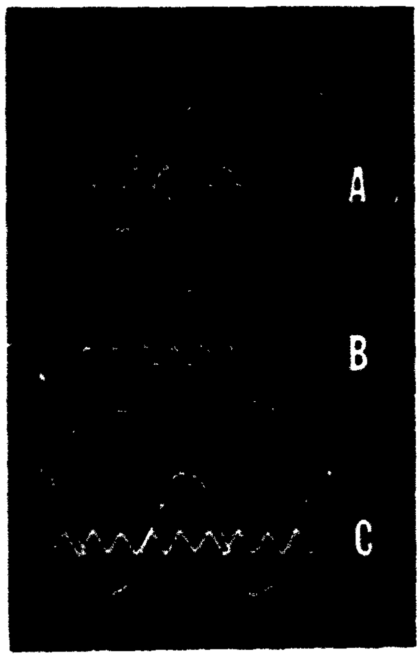

FIGURE 14 Phase Shift of 5th Harmonic

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13. ABSTRACT

A variable parameter power source was designed and fabricated to provide a 30-kva 3-phase source of power with controllable voltage modulation, frequency modulation and harmonic content for the purpose of simulating these power characteristics as described in MIL-STD-704.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
POWER PARAMETERS VARIABLE						